# USER GUIDE

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piXedfit is a Python package that provides a self-contained set of tools for analyzing spatially resolved properties of galaxies using imaging data or a combination of imaging data and the integral field spectroscopy (IFS) data. piXedfit has six modules that can handle all tasks in the analysis of spatially resolved SEDs of a galaxy, including images processing, a spatial-matching (in spatial resolution and sampling) between broad-band images and IFS data cube, pixel binning, performing SED fitting, and making visualization plots for the SED fitting results. piXedfit is a versatile tool that has been equipped with the multiprocessing module (namely message passing interface or MPI) for efficient analysis of the datasets of a large number of galaxies. Detailed description of piXedfit and its performances are presented in Abdurro’uf et al. (2021).

While this website is still under construction, people interested in knowing how piXedfit works can see some demonstrations from a folder examples on the GitHub page. Some animations can also be seen from: images processing, pixel binning and SED fitting.
Pixel binning and SED fitting
piXedfit has 6 modules that can work independently with each other such that a user interested in using a particular module in piXedfit doesn’t need to use the other modules. For instance, it is possible to use the SED fitting module for fitting observed SED, either integrated or spatially resolved SED, without the need of using the images processing and pixel binning modules. The 6 modules and their usabilities are the following:

- **piXedfit_images: image processing**
  This module is capable of doing spatial-matching (in spatial resolution and spatial sampling) of multiband images ranging from the FUV to FIR (from ground-based and spaced-based telescopes) and extract pixel-wise photometric SEDs within the galaxy’s region of interest.

- **piXedfit_spectrophotometric: spatial-matching of imaging data and the IFS data**
  This module is capable of doing spatial-matching (in spatial resolution and sampling) of a multiband imaging data (that have been processed by the piXedfit_images) with an IFS data cube (containing the same galaxy) and extract pixel-wise spectrophotometric SEDs within the galaxy’s region of interest. For the current version of piXedfit, only the IFS data from the CALIFA and MaNGA can be analyzed with the piXedfit_spectrophotometric module.

- **piXedfit_bin: pixel binning**
  This module is capable of performing pixel binning, which is a process of combining neighboring pixels to achieve certain S/N thresholds. The pixel binning scheme takes into account the similarity of SED shape among the pixels that are going to be binned together. This way important spatial information from the pixel scale can be expected to be preserved. The S/N threshold can be set to all the bands, not limited to a particular band.

- **piXedfit_model: generating model SEDs**
  This module can generate model SEDs of galaxies given some parameters. The SED modeling uses the FSPS SPS model with the Python-FSPS as the interface to the Python environment. The SED modeling incorporates the modeling of light coming from stellar emission, nebular emission, dust emission, and the AGN dusty torus emission.

- **piXedfit_fitting: performing SED fitting**
  This module is capable of performing SED fitting for input SEDs of galaxies, either spatially resolved SED or integrated SED. The input can be in the form of photometric SED or spectrophotometric SED (i.e., combination of photometry and spectroscopy). When fed with a spectrophotometric SED, piXedfit can simultaneously fit the photometric and spectroscopic SEDs.

- **piXedfit_analysis: making visualization plots for the SED fitting results**
  This module can make three plots for visualizing the fitting results: corner plot (i.e., a plot showing 1D and joint 2D posteriors of the parameters), SED plot (i.e., a plot showing recovery of the input SED by the best-fit model SED), and SFH plot (i.e., a plot showing inferred SFH from the fitting).
1.1 Installation

Currently, this Python package is only available within the collaboration. We will make \texttt{piXedfit} publicly available in timely manner. In the meantime, if you are interested in using \texttt{piXedfit}, please contact Abdurro’uf at abdurrouf@asiaa.sinica.edu.tw. We are very welcome to any ideas of new researches using \texttt{piXedfit} and we are open for collaboration.

1.2 List of imaging data

The list of imaging dataset that can be analyzed with the current version of \texttt{piXedfit} and a brief description on their specifications, unit of pixel value, and how to estimate flux uncertainty are given in the following.

- **Galaxy Evolution Explorer (GALEX)**

  The input image (in FITS) is assumed to have the same format as the one obtained from the MAST. Commonly, the background subtraction has been done for the imaging data product and the background image is provided in a separate FITS file. The imaging data in the two bands (FUV and NUV) have spatial resolution (i.e., FWHM of PSF) of 4.2" and 5.3", respectively. The spatial sampling is 1.5"/pixel. The 5\(\sigma\) limiting magnitudes in FUV (NUV) of the three surveys modes (AIS, MIS, and DIS) are 19.9 (20.8), 22.6 (22.7), 24.8 (24.4), respectively. Pixel value of the imaging data is in unit of counts (i.e., number of detected photons) per second (CPS). For more information, please refer to Morrissey et al. (2007). To convert the pixel value into flux and estimate flux uncertainty, we follow the relevant information from the literature and the survey’s website. To convert from pixel value to flux in unit of erg s\(^{-1}\)cm\(^{-2}\)Å\(^{-1}\), the following equation is used:

  \[
  \text{FUV: } \text{flux} = 1.40 \times 10^{-15} \text{CPS} \\
  \text{NUV: } \text{flux} = 2.06 \times 10^{-16} \text{CPS}
  \]

  To get flux uncertainty, first, uncertainty of counts is estimated using the following equation:

  \[
  \text{FUV: } \text{CPS}_{\text{err}} = \frac{\sqrt{(\text{CPS \times \text{exp-time}} + (0.050 \times \text{CPS \times \text{exp-time}})^2)}}{\text{exp-time}} \\
  \text{NUV: } \text{CPS}_{\text{err}} = \frac{\sqrt{(\text{CPS \times \text{exp-time}} + (0.027 \times \text{CPS \times \text{exp-time}})^2)}}{\text{exp-time}}
  \]

  The exp-time is exposure time which can be obtained from the FITS header (keyword: EXPTIME). Then flux uncertainty can be calculated using the above equations for converting from counts to flux. The above information is taken from GALEX’s website.

- **Sloan Digital Sky Survey (SDSS)**

  The input image (in FITS) is assumed to have the same format as that of the Corrected Frame product of SDSS. For this imaging data product, background subtraction has been done and the background image can be reconstructed from a cruder 2D grid of background image stored in the HDU2 extension of the FITS file. The spatial sampling of the imaging data in the 5 bands \((u, g, r, i, \text{ and } z)\) is 0.396"/pixel. The median seeing of all SDSS imaging data is 1.32" in the \(r\)-band (see Ross et al. 2011). The SDSS imaging is 95% complete to \(u = 22.0\) mag, \(g = 22.2\) mag, \(r = 22.2\) mag, \(i = 21.3\) mag, and \(z = 20.5\) mag (Abazajian et al. 2004). The pixel value in the SDSS image is counts in unit of nanomaggies. To convert the pixel value into flux in unit of erg s\(^{-1}\)cm\(^{-2}\)Å\(^{-1}\), the following equation is used:

  \[
  \text{flux} = \text{counts} \times 3.631 \times 10^6 \times 2.994 \times 10^{-5} \left(\frac{1}{\lambda_c}\right)^2
  \]

  where the \(\lambda_c\) is the central wavelength of the photometric band.

  To estimate flux uncertainty of a pixel, first, the uncertainty of counts is calculated using the following equation:

  \[
  \text{counts}_{\text{err}} = \sqrt{\frac{\text{counts}_{\text{sky}}}{\text{gain}}} + \text{dark variance}
  \]
with NMGY is a conversion factor from counts to flux in unit of nanomaggy (i.e., nanomaggy per count) and 
count_{sky} is counts associated with the sky background image. The count_{sky} at a particular coordinate in the 
image is obtained from bilinear interpolation to the cruder 2D grids of sky background counts stored in the 
HDU2 of the FITS file. Gain is a conversion factor from count to the detected number of photo electron and 
dark variance is an additional source of noise from the read-noise and the noise in the dark current. Values of 
gain and dark variance vary depending on the camera column (camcol) and the photometric band. Those values 
may be obtained from this SDSS’s web page. After getting the count_{err}, the flux uncertainty can be calculated 
using the following equation:

The above information is obtained from this SDSS’s web page.

- **Hubble Space telescope (HST)**

  The HST image has a spatial sampling of 0.06"/pixel. The PSF FWHM varies across photometric bands. The 
  PSF FWHM of F160W band is 0.19". The 5σ limiting magnitude of F160W is 26.4 mag. Pixel value of the 
  HST image is counts per second. To convert the pixel value to flux in unit of erg s^{-1}cm^{-2}Å^{-1}, a multiplicative 
  conversion factor can be found in the header of the FIST file (keyword: PHOTFLAM). Flux uncertainty of a 
  pixel can be calculated from the weight image, which commonly provided by various surveys.

- **Two Micron All Sky Survey (2MASS)**

  The input image (in FITS) is assumed to be in the same format as that provided by the NASA/IPAC Infrared 
  Science Archive (IRSA). Commonly, the imaging data from that source is not background-subtracted. The imaging 
  data product has spatial sampling of 1.0"/pixel. The seeing is ~ 2.5 – 3.5" (Skrutskie et al. 2006). The point-
  source sensitivities at signal-to-noise ratio S/N=10 are: 15.8, 15.1, and 14.3 mag for J, H, and K_{s}, respectively. 
  Pixel value of the 2MASS image is in data-number unit (DN). To convert the pixel value to magnitude, one 
  need a magnitude zero-point which can be obtained from the header of the FITS file (keyword: MAGZP). 
  Then the flux can be calculated using a flux for zero-magnitude zero-point conversion values (f_{\lambda,zero-mag}). 
  The f_{\lambda,zero-mag} in unit of W cm^{-2}μm^{-1} for the J, H, and K_{s} bands are 3.129 \times 10^{-15} \pm 5.464 \times 10^{-15}, 
  1.133 \times 10^{-13} \pm 2.212 \times 10^{-15}, and 4.283 \times 10^{-14} \pm 8.053 \times 10^{-16}, respectively (see this web page). A 
  proper conversion factor is then applied to convert the flux in the W cm^{-2}μm^{-1} to erg s^{-1}cm^{-2}Å^{-1}. The flux 
  calibration of 2MASS is described in Cohen et al. (2003). The uncertainty of pixel value in a 2MASS image is 
  estimated following the procedure described in the 2MASS survey’s website here (see the handy equations in 
  the bottom of the web page).

- **Wide-field Infrared Survey Explorer (WISE)**

  The input image (in FITS) is assumed to be in the same format as that provided in this IRSA website. Commonly, 
  the imaging data from that source is not background-subtracted. The imaging data in the 4 bands 3.4μm (W1), 
  4.6μm (W2), 12μm (W3), and 22μm (W4) have spatial resolutions of 6.1", 6.4", 6.5", and 12.0", respectively. 
  The spatial sampling of the imaging data in the 4 bands is 1.375"/pixel. WISE achieved 5σ point source sensi-
tivities better than 0.08, 0.11, 1.00, and 6.00 mJy in unconfused regions on the ecliptic in the 4 bands (Wright 
  et al. 2010). The pixel value of a WISE image is DN unit. To convert the pixel value to flux in Jy, one need 
  DN_to_Jy conversion factor. The DN_to_Jy for the W1, W2, W3, and W4 are 1.935 \times 10^{-6}, 2.7048 \times 10^{-6}, 
  1.8326 \times 10^{-6}, and 5.2269 \times 10^{-5}, respectively. The flux is then converted from Jy to erg s^{-1}cm^{-2}Å^{-1}. The 
  WISE image atlas product commonly provides uncertainty image that gives the propagated 1σ uncertainty esti-
mate for each pixel in the corresponding coadded intensity image. For estimating flux uncertainty, a relevant 
  instruction is given in a WISE survey’s website here.

- **Spitzer (IRAC and MIPS)**

  The mean FWHMs of the PSFs of the 4 IRAC bands 3.6μm, 4.5μm, 5.8μm, and 8.0μm are 1.66", 1.72", 
  1.88", and 1.98", respectively (Fazio et al. 2004). The mean FWHMs of the PSFs of the 3 MIPS bands 24μm, 
  70μm, and 160μm are 6.0", 18.0", and 40", respectively (Rieke et al. 2004). The spatial sampling of IRAC 
  imaging data is 1.2"/pixel, while the spatial sampling of MIPS imaging data varies across bands: 1.5"/pixel 
  (24μm), 4.5"/pixel (70μm), and 9.0"/pixel (160μm). The 1σ point-source sensitivities (with low background
and 100 second time frame) of the 4 IRAC bands are 0.6 μJy (3.6 μm), 1.2 μJy (4.5 μm), 8.0 μJy (5.8 μm), and 9.8 μJy (8.0 μm) (Fazio et al. 2004). The pre-launch estimate of the 1σ confusion limits of the MIPS bands are \( \sim 0.5 - 1.3 \) μJy (70 μm) and \( \sim 7.0 - 19.0 \) μJy (160 μm) (Xu et al. 2001 and Dole et al. 2003). Pixel values of the IRAC and MIPS are in unit of Mjy/sr. To convert the pixel value to flux density in erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\), one needs pixel size of the image. For estimating the flux uncertainty of a pixel, we use the uncertainty map (commonly provided by surveys, such as SINGS; Kennicutt et al. 2003) whenever available. If the uncertainty map is not available, the flux uncertainty is assumed to be dominated by the calibration uncertainty. The calibration uncertainty of the 4 bands of IRAC is \( \sim 10\% \) (Reach et al. 2005; Munoz-Mateos), whereas that uncertainties for the 3 bands of MIPS are 4% (24 μm), 5% (70 μm), and 12% (160 μm) (Engelbracht et al. 2007; Gordon et al. 2007; Stansberry et al. 2007).

- **Herschel (PACS and SPIRE)**

The three PACS bands have measured PSF FWHMs of 5.67'' (70 μm), 7.04'' (100 μm), and 11.18'' (160 μm) (Aniano et al. 2011, Geis N. and Lutz D. 2010 PACS ICC Document PICC-ME-TN-029 v2.0, Lutz D. 2010 PACS ICC Document PICC-ME-TN-033, and Müller T. 2010 PACS ICC Document PICC-ME-TN-036 v2.0). The three SPIRE bands have mean PSF FWHMs of 18.1" (250 μm), 25.2" (350 μm), and 36.6" (500 μm). The measured confusion noise levels in the 250 μm, 350 μm, and 500 μm bands are 5.8 mJy, 6.3 mJy, and 6.8 mJy, respectively (Griffin et al. 2010). The PACS imaging data has pixel value in the unit of Jy/pixel, while the SPIRE imaging data varies depending on the survey from which the data is obtained. The SPIRE imaging data provided by the Key Insights on Nearby Galaxies: A Far-Infrared Survey with Herschel (KINGFISH; Kennicutt et al. 2011) has pixel value in the unit of MJy/sr, whereas the SPIRE imaging data provided by the Very Nearby Galaxy Survey (VNGS; Bendo et al. 2012) has pixel value in the unit of Jy/beam. Based on the SPIRE Observer’s Manual, the beam areas in arcsec\(^2\) of the 250 μm, 350 μm, and 500 μm are 426, 771, and 1626, respectively. For estimating the flux uncertainty of a pixel, an uncertainty map (such as that provided by the KINGFISH and VNGS surveys) is used whenever available. Otherwise, the flux uncertainty is estimated by assuming that the flux uncertainty is dominated by the calibration uncertainty. The calibration uncertainty of PACS is \( \sim 5\% \) (according to the version 4 of the PACS Observer’s Manual), while the calibration uncertainty of the SPIRE is \( \sim 7\% \) (see this web page).

### 1.3 Available convolution kernels and PSFs

The point spread function (PSF) describes the two-dimensional distribution of light in the telescope focal plane for the astronomical point sources. To get reliable multiwavelength photometric SED from a set of multiband images, especially in the analysis of spatially resolved SEDs of galaxies, it is important to homogenize the spatial resolution (i.e., PSF size) of those images before extracting SEDs from them. This process of homogenizing the PSF size of multiband images is called PSF matching. The final/target spatial resolution to be achieved is the one that is the lowest (i.e., worst) among the multiband images being analyzed. Commonly, PSF matching process of multiband images is done by convolving the images that have higher spatial resolution (i.e., smaller PSF size than the target PSF) with a set of pre-calculated convolution kernels. The convolution kernel for matching a pair of two PSFs is derived from the ratio of Fourier transforms (e.g., Gordon et al. 2008; Aniano et al. 2011).

For PSF matching process, pixEdfit\_images module uses convolution kernels from Aniano et al. 2011 that are publicly available at this website. The available kernels cover various ground-based and spaced-based telescopes, including GALEX, Spitzer, WISE, and Herschel. Besides that, Aniano et al. 2011 also provide convolution kernels for some analytical PSFs that includes Gaussian, sum of Gaussians, and Moffat. These analytical PSFs are expected to be representative of the net (i.e., effective) PSFs of ground-based telescopes.

To associate the PSFs of SDSS and 2MASS (which are not explicitly covered in Aniano et al. 2011) with the analytical PSFs of Aniano et al. 2011, we have constructed empirical PSFs of the 5 SDSS bands and 3 2MASS bands and compare the constructed empirical PSFs with the analytical PSFs from Aniano et al. 2011. We find that the empirical PSFs of SDSS \( u \), \( g \), and \( r \) bands are best represented by double Gaussian with FWHM of 1.5", while the other bands \( (i \ and \ z) \) are best represented by double Gaussian with FWHM of 1.0". For 2MASS, all the 3 bands \( (J, H, \) and \( K_S) \) are best represented by Gaussian with FWHM of 3.5". Construction of these empirical PSFs is presented
in Appendix A of Abdurro’uf et al. (2020, submitted). The empirical PSFs are available at this Github page. For consistency, the *pixedfit* use those analytical PSFs to represent the PSFs of SDSS and 2MASS and use the convolution kernels associated with them whenever needed.

By default, when external kernels are not provided by the user, *pixedfit* module will use the kernels from Aniano et al. 2011. For flexibility, the users can also input their own kernels to *pixedfit*.

Figures below show a demonstration of the performance of some convolution kernels used in the *pixedfit* module. In the top figure, the performance of the convolution kernels used to achieve the spatial resolution of WISE/W2 is demonstrated. Different panels show different initial PSFs. In the first row from the left to right, we show the convolution results from initial PSFs of GALEX/FUV, GALEX/NUV, and SDSS/\(u\), respectively. The second row, from left to right, we show the result for SDSS/\(z\), 2MASS/\(J\), and 2MASS/W1, respectively. In the bottom figure, the performance of the convolution kernels used to achieve the spatial resolution of Herschel/SPIRE350 is demonstrated. In the first row from the left to right, we show the convolution results from initial PSFs of GALEX/FUV, SDSS/\(u\), and 2MASS/\(J\), respectively. The second row, from left to right, we show the result for WISE/W1, Spitzer/IRAC 8.0\(\mu m\), and Spitzer/MIPS 24\(\mu m\), respectively. The figures shows that the performance of the convolution kernels is very good, evidenced from the good matching between the shapes of the convolved PSFs and the target PSF.
For the characteristic PSFs of the imaging data that can be analyzed with the current version of piXedfit, please see the description in this page.

1.4 Image processing

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1.4.1 Background subtraction

1.4.2 Deriving variance Images

1.4.3 Running image processing

1.4.4 Output format

1.5 Matching imaging data with IFS data

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1.6 Pixel binning

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1.7 Ingredients in SED modeling

In piXedfit, the task of generating model SEDs is done by piXedfit_model module. The SED modeling uses the Flexible Stellar Population Synthesis (FSPS) package through the Python-FSPS as the interface to the Python environment. The FSPS package provides a self-consistent modeling of galaxy’s SED through a careful modeling of the physical components that make up the total luminosity output of a galaxy, which consist of stellar emission, nebular emission, dust emission, and emission from the dusty torus heated by the AGN. Since piXedfit_model module uses the FSPS model, every parameter (i.e., ingredient) available in the FSPS is also available in the piXedfit_model.

1.7.1 SSP model

For modeling a Simple Stellar Population (SSP), the FSPS provides several choices for the Initial Mass Function (IMF), isochrones calculation, and the stellar spectral libraries. The Chabrier et al. (2003) IMF, Padova isochrones (Girardi et al. 2000; Marigo et al. 2007; Marigo et al. 2008), and MILES stellar spectral library (Sanchez-Blazquez et al. 2006; Falcon et al. 2011) are used as the default set in the piXedfit_model, but in principle, all the choices available in the FSPS (python-FSPS) are also available in the piXedfit_model. In practice, SED fitting procedure demands model SEDs with a random set of \( Z \) rather than in a discrete set, as given by the isochrones. In this case, we choose an option in FSPS that allows interpolation of SSP spectra between \( Z \) grids. Users of piXedfit_model can choose from the 5 available choices of IMF that FSPS provides: Salpeter et al. (1955), Chabrier et al. (2003), Kroupa et al. (2001), van Dokkum et al. (2008), and Dave (2008).

FSPS uses the CLOUDY code (Ferland et al. 1998, 2013) for the nebular emission modeling. The implementation of CLOUDY within FSPS is described in Byler et al. (2017). In short, the modeling has three parameters: SSP age, gas-phase metallicity, and the ionization parameter, \( U \), which represents the ratio of the ionizing photons to the total hydrogen density. By default, the gas-phase metallicity is set to be equal to the model stellar metallicity, and \( U \) is fixed to 0.01. The user can also set them as free parameters in the fitting, preferentially if a constraining data is available (e.g., deep optical spectra). The modeling has incorporated the dust attenuation to the emission lines.

There are five options for the dust attenuation modeling in FSPS. We only accommodate two of them in piXedfit_model: Calzetti et al. (2000) and the two-component Charlot & Fall (2000) dust attenuation model.

In brief, the Calzetti et al. (2000) assumes equal dust attenuation over all starlight regardless of the stellar ages, while Charlot & Fall (2000) assumes an extra attenuation for the light coming from young stars (typically younger than 10 Myr) which still reside in the birth-cloud. For the Calzetti et al. (2000) dust attenuation model, only one parameter is involved, \( \tilde{\tau}_2 \), which represents the dust optical depth. For the two-component Charlot & Fall (2000) model, there are three parameters involved: (1) \( \tilde{\tau}_1 \) controls normalization of the attenuation curve for the birth-cloud component, (2) \( \tilde{\tau}_2 \) controls the normalization of the attenuation curve for the diffuse interstellar medium (ISM) component, and (3) the power-law index \( n \) in the dust attenuation curve for the diffuse component (see Eq. 7 and 8 in Leja et al. 2017).

1.7.2 Choices for the SFH

piXedfit adopts the parametric star formation history (SFH) approach, which assumes a functional form for the SFH when generating the model SED of a Composite Stellar Population (CSP). In piXedfit_model, there are 5 choices of SFH available:

- **Tau model**
  \[
  SFR(t) \propto e^{-t/\tau}
  \]
  The \( \tau \) represents the timescale for the declining of the star formation.

- **Delayed tau**
  \[
  SFR(t) \propto t e^{-t/\tau}
  \]
  The \( \tau \) is a parameter that controls the duration of the star formation.
• **Log-normal**

\[ SFR(t) \propto \frac{1}{t} \exp \left( -\frac{(\ln(t) - T_0)^2}{2\tau^2} \right) \]

The free parameters \( T_0 \) controls the peak location, while \( \tau \) controls the duration of the star formation.

• **Gaussian**

\[ SFR(t) \propto \exp \left( -\frac{(t - T_0)^2}{2\tau^2} \right) \]

The \( T_0 \) represents the time when star formation reaches the peak, while the \( \tau \) controls the duration of the star formation.

• **Double power law**

\[ SFR(t) \propto \left( \frac{1}{t} \right)^\alpha + \left( \frac{1}{t} \right)^{-\beta} \]

The \( \alpha \) and \( \beta \) are the falling slope, and the rising slope, respectively. The \( \tau \) parameter controls the peak time.

All the \( t \) in the above equations represent the time since the start of star formation (i.e., age of the system, \( \text{age}_{\text{sys}} \)). The following figure shows examples of SFHs formed with the 5 SFH choices. All the model SFHs have the same age \( t \) of 12.5 Gyr and \( M_* = 5.0 \times 10^{10} M_\odot \). The other SFH parameters are: tau model \( [\tau = 4.0 \text{ Gyr}] \), delayed tau \( [\tau = 2.5 \text{ Gyr}] \), log-normal \( [\tau = 1.0 \text{ Gyr}, T_0 = 1.3 \text{ Gyr}] \), Gaussian \( [\tau = 2.5 \text{ Gyr}, T_0 = 7.0 \text{ Gyr}] \), and double power law \( [\tau = 2.5 \text{ Gyr}, \alpha = 2.0 \text{ Gyr}, \beta = 2.0 \text{ Gyr}] \).

1.7.3 Dust emission and AGN components

The dust emission modeling in FSPS assumes the energy balance principle, where the amount of energy attenuated by the dust is equal to the amount of energy re-emitted in the infrared (IR) (da Cunha et al. 2008). FSPS uses the Draine & Li (2007) dust emission templates to describe the shape of the IR SED. There are three parameters in the dust emission modeling: \( U_{\text{min}}, \gamma_e, \) and \( Q_{\text{PAH}} \). \( U_{\text{min}} \) represents the minimum starlight intensity that illuminate the dust. This minimum starlight intensity is typically found in the diffuse ISM. \( \gamma_e \) represents the fraction of dust mass that is exposed to this minimum starlight intensity. \( Q_{\text{PAH}} \) represents the fraction of total dust mass that is in the polycyclic aromatic hydrocarbons (PAHs).

For the modeling of emission from the dusty torus heated by the AGN, FSPS uses AGN templates from the Nenkova et al (2008a, b) CLUMPY models. The CLUMPY model uses radiative transfer techniques to approximate the SED from...
the clumpy dust torus medium which is illuminated by light from the AGN with a broken power-law spectrum. The CLUMPY AGN model is included in the FSPS based on some assumptions that are described in Leja et al. (2018). The modeling has two free parameters: $f_{\text{AGN}}$ which represents the total luminosity of the AGN, expressed as a fraction of the galaxy bolometric luminosity, and $\tau_{\text{AGN}}$ which represents the optical depth of an individual dust clump at 5500Å in the dusty torus.

1.7.4 IGM absorption, redshifting, and convolving with filters

The piXedfit model has two options for the IGM absorption: Madau (1995) and Inoue et al. (2014). After applying the IGM absorption, the effect of cosmological redshifting and dimming is then applied to the model spectra. After this process, the spectra is transformed into the observer frame flux density ($f_\lambda$). Typically, this calculation requires redshift information of the galaxy. Whenever provided, input redshift (if spectroscopic redshift is available) is used. Otherwise, redshift is set as a free parameter in the fitting. The calculation of the luminosity distance uses the cosmology package in the Astropy. The final step in generating model photometric SEDs is convolving the model spectra with the set of filter transmission functions. The current version of piXedfit has 163 photometric filters of ground-based and space-based telescopes. The user can also add a filter transmission function using add_filter() function in filtering module.

1.8 Generating model SEDs

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1.9 Fitting spatially resolved SEDs

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1.10 Fitting integrated SEDs

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1.11 Plotting fitting results

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1.12 Obtaining spatially resolved maps of properties

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1.13 Demonstration of images processing

The animations below demonstrate the images processing of NGC309 (top) and M51 (bottom). In the animations, images produced at each step in the images processing are shown. Overall, the steps in images processing, especially that are shown (highlighted) in this animation are: cropping, PSF matching, reprojection and spatial resampling.

If the animations above don’t play, please see from here.

1.14 Demonstration of the pixel binning process

The animation below shows demonstration of how our new pixel binning scheme works. The pixel binning is done using the piXedfit_bin module. Basically, the pixel binning starts from a brightest pixel (in a reference band, which is selected by the user) then surrounding pixels (within a certain dimeter) that have SEDs with similar shape as the SED of the brightest pixel are binned together. If the resulted S/N in each band is still lower than a given S/N threshold, then the bin’s size is increased gradually with increment radius of 2 pixels until the S/N thresholds in all bands are achieved.

In the animation below, a pixel binning process of the NGC309 (top) and M51 (bottom) galaxies are demonstrated. For the NGC309, we use 12-band imaging data from GALEX, SDSS, 2MASS, and WISE, while for the M51, we use panchromatic imaging data in 23 bands ranging from GALEX/FUV to Herschel/SPIRE350. Before the pixel binning, the multiband images are processed (i.e., spatially-matched in spatial resolution and spatial sampling) using the piXedfit_images module. In each row, the left panel shows SDSS/r image, which is the reference band in
this pixel binning process. The middle panel shows the binning map that is being constructed. The right panel shows SEDs of pixels (in colors) that are belong to a bin and the total SED of a bin (in black color).

If the animations above don’t run, please see from here.

## 1.15 Demonstration of SED fitting

### 1.15.1 The MCMC process

Animation below shows a demonstration of the MCMC process in an SED fitting using the `piXedfit_fitting` module. For this example, the SED fitting is done to a mock photometric SED covering GALEX/FUV to Herschel/SPIRE250.

If the animation doesn’t run, please see the animation here.

After each MCMC walker has done a certain number of steps, the MCMC process is terminated. Then we get the distributions of sampler chains, i.e., record of visited locations by the MCMC walkers in the N-dimensional parameter space. By making density plot out of the sampler chains, we can get posteriors probability distributions as shown below (the corner plot). The SED plot shows best-fit model SED obtained from the posteriors.

In the corner plot, the red vertical lines are the true parameters of the mock SED. The vertical black dashed lines and blue dashed lines are medians and modes of the posteriors. The gray shaded areas are the 16th-84th percentiles representing uncertainties. In the SED plot, the blue squares show the mock photometric SED. The best-fit model SED (black spectrum) is further broken down into its components: stellar emission (yellow), dust emission (red), AGN dusty torus emission (green), and nebular emission (cyan). The dashed spectral components represent the true mock SED, while the solid ones show the best-fit model SED.
1.15.2 The effect of wavelength coverage

The following animation demonstrates the effect of the wideness of the wavelength coverage and also the wavelength sampling of the photometric SED on the resulting posteriors probability distributions in the SED fitting. As we can see, the constraining power is enhancing (shown by the increasing convergence of the posteriors probability distributions) as increasing number of photometric points and expanding wavelength coverage.

1.16 Tutorials

(This page is still under construction!)

1.16.1 Image processing

1.16.2 Spatial matching between imaging data and IFS data

1.16.3 Pixel binning

1.16.4 SED fitting

1.16.5 Making corner plot, SED plot, and SFH plot

1.17 piXedfit_images

(This page is still under construction!)
1.18 piXedfit_spectrophotometric

(This page is still under construction!)

1.19 piXedfit_bin

(This page is still under construction!)

1.20 piXedfit_model

(This page is still under construction!)

1.21 piXedfit_fitting

(This page is still under construction!)

1.22 piXedfit_analysis

(This page is still under construction!)
1.22. piXedfit_analysis
A list of some projects piXedfit is benefitted from:

- FSPS and Python-FSPS stellar population synthesis model
- emcee package for the Affine Invariant Markov Chain Monte Carlo (MCMC) Ensemble sampler
- Astropy
- Photutils
- Aniano et al. (2011) who provides convolution kernels for the PSF matching
- SExtractor (Bertin & Arnouts 1996)
- Abdurro’uf & Akiyama (2017, 2018)